MODELLING THE SURVIVAL OF CARBONACEOUS CHONDRITES IMPACTING THE LUNAR SURFACE AS A POTENTIAL RESOURCE. S. H. Halim[1] (shalim03@mail.bbk.ac.uk), I. A. Crawford[1], G. S. Collins[2], K. H. Joy[3], T. M. Davison[2]. [1]Birkbeck, University of London, UK. [2]Imperial College London, UK. [3]University of Manchester, UK.

Introduction: The surface of our closest celestial neighbour is increasingly becoming a prime target for the next step in human exploration, with an emphasis on developing approaches for *in situ* resource utilisation (ISRU). Whilst the lunar surface may potentially provide an abundance of extractable metals [1,2], water [3-5], and potential construction materials for lunar habitats [6], there is a lack of a number of key elements in enough quantities needed to facilitate a long-term, sustainable human presence on the Moon [7]. Carbon and nitrogen are two such elements. These have been potentially delivered to the Moon in the form of carbonaceous chondrite (CC) meteorites [8,9]. The rich impact history of the Moon indicates that CC meteorites will have impacted the lunar surface at some point over geological time and could, therefore, be a source of these key elements if they survive [10, 11].

In the context of using CC material as a resource for lunar surface operations, it is important to consider where the material remains concentrated post-impact. If the material 'survives' (according to the pressure and temperature regimes recorded within the projectile), but is dispersed over a wide area after impact, it becomes less economical to collect and use as a resource. However, if a significant amount of material is concentrated within a small area surrounding the impact site (e.g., a few km), it could become an attractive resource and a potential target to establish a nearby lunar outpost.

Investigation of both the temperature regimes and the location of CC material post-impact requires a suite of 3D impact models at a variety of impact angles and velocities. Here, we concentrate on the survival of carbon-bearing molecules as they are more abundant than nitrogen within CCs [9] and are more likely to survive impact due to their physical properties [8,9] (Table 1).

Methods: Using iSALE-3D [12], we modelled the impact of a 1 km diameter CC-like asteroid into a single-layer, basaltic lunar surface. The simulation used a resolution of 16 cells per projectile radius, using the ANEOS equation of state (EoS) for serpentine [13] to best approximate CM CC-material and the ANEOS basalt EoS [14] to represent the lunar surface. Porosity was included in both impactor and target, with porosities chosen based on average values for CC parent bodies [15] (40%) and the lunar megaregolith [16] (10%).

Impact velocities of 10 and 15 km/s were tested, with impact angles varied between 15 and 60º to the horizontal, at 15º increments. Lagrangian tracer particles were placed in each cell of the projectile to track temperature, pressure, and the location of the material over the course of the impact. Peak shock temperatures were then compared to vaporization temperatures for known carbon bearing molecules in CCs (Table 1).

Table 1: Average abundance for types of carbon found in CM, CI, CO, CR, and CV CCs. [8]

Carbon type	Abundance (wt%)	Approximate vaporisation temp (K)
Organic matter	2.0	550-750[8]
Carbonate	0.2	700-1000[8]
Diamond	0.04	4000[17]
Graphite	0.005	4000[17]
Silicon carbide	0.009	3000[18]

Results: Even in the scenario with the most oblique impact angle and the lower velocity (15º and 10 km/s), over 99% of the projectile experiences temperatures >700 K. Therefore, it is highly unlikely that any carbonate or organic matter could survive in any impact scenario we tested. However, the high vaporisation temperatures of diamond, graphite, and silicon carbide, allow for the possibility of some carbon bearing material to survive after impact. In the following figures, we show the final location of projectile material experiencing peak temperatures of <2000 K by the end of the simulation. Although 2000 K seems significantly lower than the vaporisation temperatures (where you would expect material to be lost to space), it was chosen as it is also below the melting temperature of the serpentine material used (2173 K). Therefore, the likelihood for carbonaceous material to remain within the landed projectile material is increased as it is likely to be solid.

Fig. 1 shows the results for the simulations where carbon-bearing material survives. All plots show the location of material at the end of the calculation, where most projectile material has stopped moving, however some material is still moving away from the impact site, especially in the most oblique impacts. More time is needed to run the calculations to completion. Fig. 1a shows the best scenario for the survival of carbon-bearing material, a highly oblique, low-velocity impact (15º, 10 km/s). Increasing the velocity leads to a decrease in the proportion of projectile material experiencing <2000 K (Fig 1b), however ~30% of the projectile material still survives. This spreads over a very large area, with the bulk of the material concentrating ~15 km from the impact point, especially in Fig. 1a. Increasing impact angle to 30º leads to a marked decrease in the amount of solid projectile material suitable for carbon molecule survival (Fig. 1c and 1d), with material concentrated within the craters (~3.5 and ~4.8 km down-range diameters, respectively). For impact angles of 45º and 60º, the proportion of material experiencing temperatures <2000 K

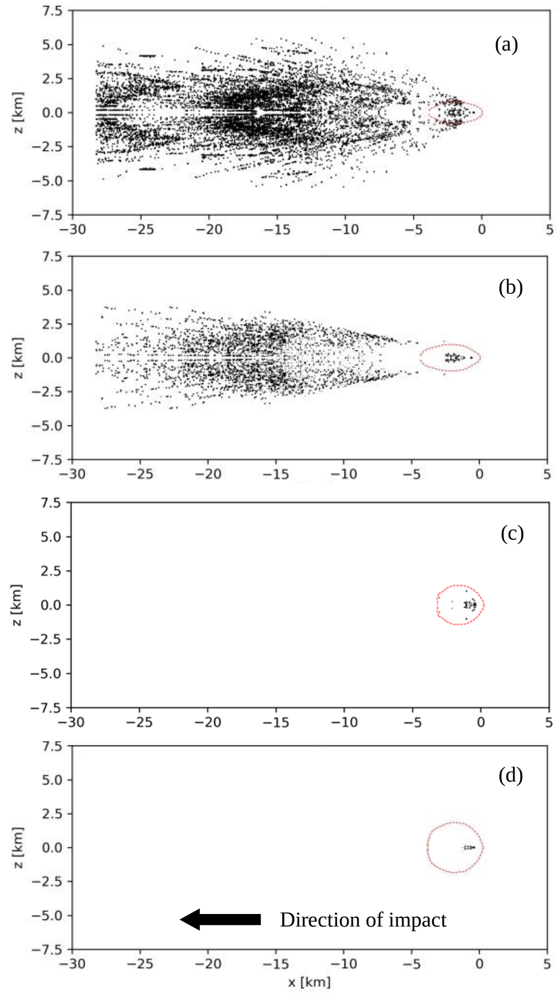

Fig 1: *Plan-view, location plots of projectile material experiencing peak temperatures <2000 K. Impact initially occurs at point [0, 0]. Each black dot represents a block with original dimensions 30x30x30m. (a) 15º, 10 km/s, (b) 15º, 15 km/s, (c) 30º, 10 km/s, (d) 30º, 15 km/s. Red dashed lines represent the approximate shape of the crater.*

becomes insignificant at both velocities tested. The large discrepancy between the proportion of carbon-suitable material surviving at highly oblique and less oblique angles is likely due to a combination of factors. Firstly, the vertical component of the velocity is decreased compared to more direct impacts. This leads to less energy imparted into the projectile after initial contact with the target surface and therefore lower pressures and temperatures across a large volume of the projectile [19]. Additionally, a process called "projectile decapitation" [20] can remove a large proportion of the projectile after the initial impact which later impacts downrange at a lower velocity. This process can be seen in our highly oblique (15º) impact (Fig. 2).

Conclusions: Carbonaceous chondrites impacting into the lunar surface at highly oblique angles show promising results for the survival of carbon-bearing material. However, the material covers vast areas, over 25 times the projectile diameter downrange with the majority of material at a distance of ~15 projectile diameters. Less oblique impacts (>30º) concentrate the material close to and within the resulting crater, but greatly reduce the amount of suitable surviving material. There is room for expansion in the suite of models to find the "sweet spot" where surviving carbonaceous material is concentrated sufficiently to be useful as a resource. A reasonable assumption is that this spot lies between 15-30º at a low, but not unlikely, velocity (e.g., 10 km/s) or at a less oblique angle (45-60º), at a much lower velocity (<<10 km/s) [21]. Further models will be simulated to investigate.

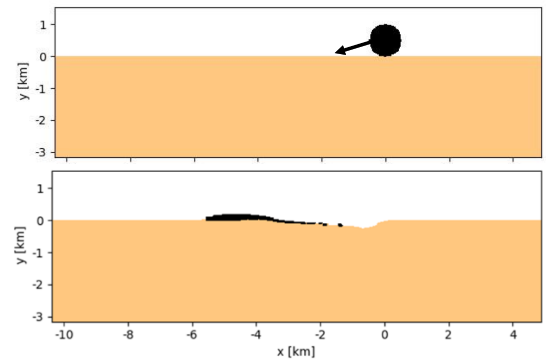

Fig 2: *Top: cross-sectional, pre-impact view of the scenario shown in Fig. 1a. (15º, 10 km/s). Below: immediately after impact (0.5s). Black highlights the surviving projectile material, a large proportion of which travels away from the crater.*

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